EVLA and LWA Imaging Challenges

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EVL A key issue s
Key algorithmic issues

Ambitious goals / hard problems

- high-dynamic range imaging
  - faint emission in the presence of bright sources
  - direction dependent aberrations (pointing errors, ionosphere)
  - polarized primary beam corrections
  - makes everything more difficult

- wide-field imaging
  - important at low frequencies & high resolution
  - faceting & w-projection are the state-of-the-art solutions

- wide-band imaging
  - important in all bands, particularly in 2:1 bands (1-2, 2-4, 4-8 GHz)
  - image spectral index & faraday rotation
  - multi-frequency synthesis (MFS) as starting point
  - often necessary to combine with multi-scale imaging
Key algorithmic issues

ambitious goals / hard problems

• multi-scale imaging
  – emission on wide range of angular scales (e.g. Galactic Center)
  – minimize deconvolution artifacts (e.g. clean bowls)
  – Multi-Scale Clean (MSClean) an example
  – area for active research
• multi-field imaging (mosaicing)
  – observe multiple fields to synthesize larger field of view
  – important at high frequencies (key for ALMA)
• multi-plane imaging
  – ionosphere appears as volume over array (low frequencies)
    • limits isoplanatic field-of-view at long baselines (>km)
  – troposphere phase screen (high frequencies)
  – RFI multi-path from horizon or within array
Key computing issues

high data rates and volumes

• The problem…
  – 8h, VLA-A, LBand data processed in ~10h (20GB)
    • Corresponds to about 1% of the EVLA data
  – 2008 spec 25 MB/s max (cf. VLA 0.1 MB/s)
  – WIDAR can produce much higher rates!
  – data volumes also (TB datasets)

• solution: archive
  – use ALMA archive development where possible

• solution: computational muscle
  – high data rates and processing loads for hard problems
  – parallel coding for cluster environments

• solution: i/o bandwidth
  – parallel file systems
  – i/o balanced parallelization of algorithms
LWA key issues
LWA Special Issues

• inherits many of the problems of low-frequency EVLA
  – and adds new ones!
• the sky is full of sources
  – multi-scale emission, wide dynamic range
• the ionosphere is dynamic
  – strongly dispersive
  – must be reconstructed along with sky (on coherence timescale)
• the instrument response is variable
  – station beams must be calibrated and controlled
• the RFI environment is brutal
  – from all over NM, within an extended LWA, multi-path
The State of the Art
Limits to wide field imaging quality

- Deconvolution of extended emission
- Non coplanar baselines
- Pointing errors
- Time-variable primary beams/station calibration errors
- Non-isoplanatism (e.g. ionosphere, troposphere)
- RFI mitigation
- Polarized primary beams
- Spectral indices and rotation measure of sources
- Missing short-spacing data
- Computing costs (software and hardware)
Deep VLA image at 1.4GHz: 3µJy

- 120h integration with Very Large Array
- EVLA 3-10 times deeper
- SKA will go 10 times deeper in a few hours
- Already limited by pointing errors?
Galactic plane at 90cm

- Nord *et al.* observations
- AIPS IMAGR program using faceted transforms (Cornwell and Perley 1992)
- Poor deconvolution of extended emission
- Facet boundaries obvious
State of the Art: Wide-field image

- VLA B, C, D
- \( \lambda 90 \text{cm} \)
- Imaged using W-projection to counter non-coplanar baselines effect
- Deconvolved using Multi-scale CLEAN
Paths to the Solutions
Wide Field Imaging

• Traditional approach (Faceted imaging)
  – Approximate the sky as smaller facets
  – Use 2D approximation within the facets
  – Stitch the facets together to make the final image

• Problems
  – Multiple gridding/de-gridding per major cycle
  – Edge effects
  – Extended emission across facets

• Solutions
  – Would like to grid to single uv-plane (minimize faceting)
  – W-projection (Cornwell, Golap & Bhatnagar: EVLA Memo 67)
  – Spherical harmonic transforms (Prasad)
Wide-field: spherical sky geometry

- **spherical sky:**
  - unit sphere
  - modes are spherical harmonics

- **projection:**
  - onto tangent plane
  - modes are Fourier
  - direction cosines
  - $\xi = (\xi, \eta, \zeta)$

- **aperture uv-plane:**
  - $\mathbf{u} = \mathbf{B} / \lambda$
  - $\mathbf{u} = (u, v, w)$

- **project plane-wave onto baseline vector**
  - phase $2\pi \xi \cdot \mathbf{u}$
  - looks like Fourier transform

$$1 + \zeta = \sqrt{1 - \xi^2 - \eta^2}$$
Wide-field: effect of “w-term”

- For wide fields, the relationship between sky and visibility is no longer a 2D Fourier transform

- If we use a 2D Fourier transform, point sources away from the phase center of a radio synthesis image are distorted
  - convolved with ringing pattern

- Bad for long baselines, large field of view, and long wavelengths
  - “non-coplanar” baselines

\[
V(u, v, w) = \int I(l, m) e^{j2\pi(u(l + v) + w(\sqrt{1-l^2-m^2} - 1))} \, dl \, dm
\]
Wide-field: W-Projection

- Use Fresnel term during gridding
  - Project w-axis onto w=0 plane during gridding.
  - Use average PSF during minor cycle.
- Advantages
  - Major cycle speed-up ~10x.
  - No edge effects. User always sees 2D projection.
  - Component based imaging (MS-Clean, Asp-Clean) possible.
  - Implemented in CASA

(see talk by Kumar Golap)
Wide-Band Imaging

- Many next generation instruments rely upon increased bandwidth for improved continuum sensitivity
- Source spectral index and polarization variations over band and position
- Solve for spectral index or rotation measure images
  - fewer parameters than channels
  - but effective array (uv-coverage) changes over band!
- Multi-frequency synthesis (MFS)
  - construct derivative image (e.g. dI/dv)
  - e.g. Conway, Cornwell & Wilkinson (1990)
    - see Urvashi’s talk
- Critical for EVLA, LWA, eMERLIN, SKA …
Multi-scale imaging

• Problem: reconstruct image of sky given data and errors
  – “best” image? or “plausible” image? what about uncertainties?
• Mathematics: know map between data and image and model
  – model space need not be image space (hidden)
  – vis data ← FT sky ↔ sky image ← model
  – forward “prediction” from model to data
    • want to solve inverse problem: from data to model
    • for non-orthonormal model bases, only forward map to image

D ← I ← M
Multi-scale imaging

- Limitation: there are unconstrained modes in the sky
  - interferometry: gaps in uv-coverage
  - convolution due to aperture illumination function ("beam")
- Model Basis: the sky is not filled with point sources!
  - CLEAN and MEM use point sources (pixels) as basis functions
    - complete basis – unique representation of image
    - use point and extended basis functions
      - over-specified set of functions
      - most efficient if sets are as distinct as possible
  - MS-Clean: use Gaussians on grid of scales
    - wish list: MS-MEM
MEM and CLEAN

• CLEAN
  – basis: delta functions (on pixels)
  – algorithm:
    • find peak in residual image; add fraction to model; form new residual data, update residual image; iterate
  – performance:
    • good on compact emission, difficult for extended

• Maximum Entropy Method (MEM)
  – basis: pixels
  – algorithm:
    • for pixel values \( p \): maximize entropy \(-\Sigma p \ln p\); minimize \( \chi^2(p) \)
  – performance:
    • complicated, suppresses spiky emission, but fast
Sparse Approximation Imaging

- Problem: find a model to represent the sky as efficiently as possible, subject to the data constraints and within the noise uncertainty, possibly also subject to prior constraints.
  - some problems (like ours) cannot be efficiently reconstructed using orthonormal bases (like pixels or Fourier modes)
  - extensive literature on this!
  - use non-orthogonal bases: multiscale (e.g. Gaussians)
  - choose dictionary of model elements (atoms)
  - efficiency: find a representation that uses the fewest number of atoms

- Algorithms
  - mostly iterative, starting from a blank model
  - “greedy” methods make locally optimal choices at each step
  - MS-CLEAN is a greedy algorithm in this class!
    - is essentially a “Matching Pursuit” (MP) algorithm (e.g. Tropp 2004)
Example: MEM versus CLEAN

Restored

Residual

Error

Maximum Entropy

MS Clean

[Images of restored, residual, and error images for MEM and MS Clean conditions]
Pointing self-calibration

- Determines pointing errors directly from visibilities and component model
- Model = 59 sources from NVSS: 2 to 200mJy
- Bottom shows pointing offsets and residuals

\[ \tilde{E}_i \otimes \tilde{E}_j^* = \left[ \frac{1}{\sigma} \sqrt{\frac{\pi}{2}} e^{-\frac{u^2\pi^2}{2\sigma^2}} \right] e^{i \pi u \cdot (\tilde{\alpha}_i + \tilde{\alpha}_j)} \]

- See Bhatnagar, Cornwell, and Golap, *EVLA memo 84*
Expected level of performance

- Simulation of EVLA observations at 1.4GHz
- Residual images
  - Before correction
    - Peak 250\(\mu\)Jy, RMS 15\(\mu\)Jy
  - After correction with estimates of pointing errors
    - Peak 5\(\mu\)Jy, RMS 1\(\mu\)Jy
- Can incorporate into standard self-calibration procedures
- Affordable
- Implementing in CASA by Bhatnagar (soon!)
Primary Beam: full field polarization

- VLA primary beams
  - Beam squint due to off-axis system
  - Instrumental polarization off-axis
  - Az-El telescopes
- Instrumental polarization patterns rotate on sky with parallactic angle
  - Limits polarization imaging
  - Limits Stokes I dynamic range (via second order terms)
  - Must implement during imaging

Green contours: Stokes I 3dB, 6dB, black contours: fractional polarization 1% and up, vectors: polarization position angle, raster: Stokes V
Simulations on a complex model

- VLA simulation of ~ 1 Jy point sources + large source with complex polarization (“Hydra A”)
- Long integration with full range of parallactic angles
- Equivalent to weak 1.4GHz source observed with EVLA
- Antenna primary beam model by W. Brisken
- See EVLA memo 62
Polarization dynamic range ~ 200 when using symmetrical antenna beam model
Polarization dynamic range ~ 10,000 using two-dimensional primary beam model
Special Problem: Station Beams

SKA LNSD station beam compared to ideal primary beam – also LWA, LOFAR, etc.

PB for 80m filled aperture

PB for 13 element station

Calibration errors will move the main lobe and sidelobes around
Ionosphere: Non-isoplanatism

- VLA refractive wander at 74MHz
  - Cotton’s Field Based Calibration algorithm can correct
- Defocusing on baselines >10km
  - No known algorithm
- Will limit dynamic range at meter wavelengths
- Likely to be very expensive computationally
- Critical for LWA
- New approaches
  - reconstruct ionospheric volume above array
  - (A. Datta talk & thesis)

For baselines > 100km the ionosphere looks like a 3D volume above the array
Correcting the Ionosphere

**Problem**
- At 74 MHz, phase distortions vary across the FOV

**Solution: Field Based Calibration**
- Take snapshot images of bright sources in the field and compare to NVSS positions
- Fit a 2nd order Zernike polynomial phase delay screen for each time interval
- Apply time varying phase delay screens while imaging

*Work by Cotton and Condon*

*Slide from Aaron Cohen*
RFI: Mitigation and Removal

- Active and Passive methods
  - active: use reference horns, other hardware
  - passive: use data itself & structure of imaging equations

- Appears as extra “plane” in imaging equations
  - can be in near field: spherical wavefronts (Fresnel diffraction)
  - If the integration time is sufficiently short then interference will close
    - passive: use closure properties to identify and remove RFI
  - signature of RFI is that it has zero fringe frequency
  - for broad band, can also identify location e.g. on horizon, in array

- RFI is filtered through far sidelobes of the array antennas
  - passive: use array as its own reference

- Many issues
  - signal headroom, multi-path and reflections
RFI: excision by partitioning

**Measurement equation**

\[ V_{ij}^{\text{obs}} = g_i g_j^* V_{\text{source}} + a_i a_j^* k_i k_j^* P \]

**Gain solution**

\[ S = \sum_{ij} w_{ij} \left| V_{ij}^{\text{obs}} - g_i g_j^* V_{\text{model}} - a_i a_j^* k_i k_j^* \right|^2 \]

**Gain application**

\[ V_{ij}^{\text{cal}} = \left( g_i g_j^* \right)^{-1} \left( V_{ij}^{\text{obs}} - a_i a_j^* k_i k_j^* P \right) \]

- Antenna gain
- Antenna sidelobe gain
- RFI power
- Propagation term
RFI: VLA example

• try partitioning (peeling) to knock down interference

Channel 60: -20 db is not enough
RFI: VLA example continued

- Method likely to work well for low-level residual RFI

Use as second line of defense on low level dilute RFI left over by other approaches

Channel 75: ~7db lower, good!

Channel 70-80: even better!
Conclusions
The Tip of the Iceberg

• A number of challenging imaging issues identified
• Some possible solutions and avenues for exploration identified
• Many problems in common for next generation instruments
  – wide-field wide-band high-dynamic range high-fidelity…
  – extremely high data rates and volumes
• Opportunities for collaboration between projects!
  – LWA and EVLA natural partners
  – also ATA, RadioNET (LOFAR, eMERLIN), SKA (Koalas, Meerkats)
• My own view
  – challenges are mostly algorithmic at this point
  – software package agnostic – develop in whatever you are comfortable with!
  – new frameworks & data models MAY allow interchange